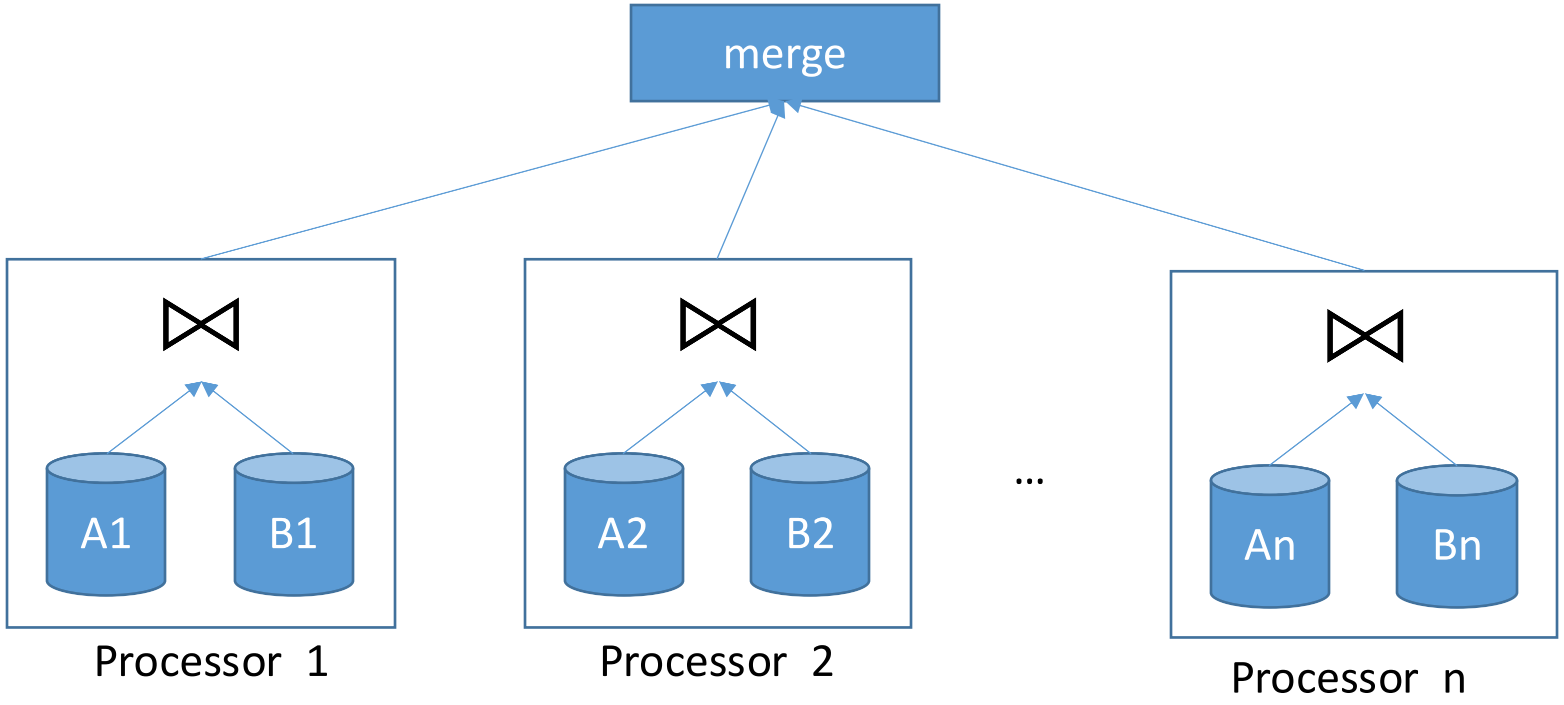
Lecture 16: Parallel and Distributed Databases

“two phase commit distributed transaction in early netherlandish style”
Stable Diffusion, November 8, 2022 at 1:52PM

Parallel DB Recap

- Last time: discussed parallel query execution
- Focused on *partitioned parallelism*



Partitioning Strategies

- **Random / Round Robin**
  - Evenly distributes data (no skew)
  - Requires us to repartition for joins
- **Range partitioning**
  - Allows us to perform joins without repartitioning, when tables are partitioned on join attributes
  - Subject to skew
- **Hash partitioning**
  - Allows us to perform joins without repartitioning, when tables are partitioned on join attributes
  - Only subject to skew when there are many duplicate values

Parallel Operations in a Partitioned DB

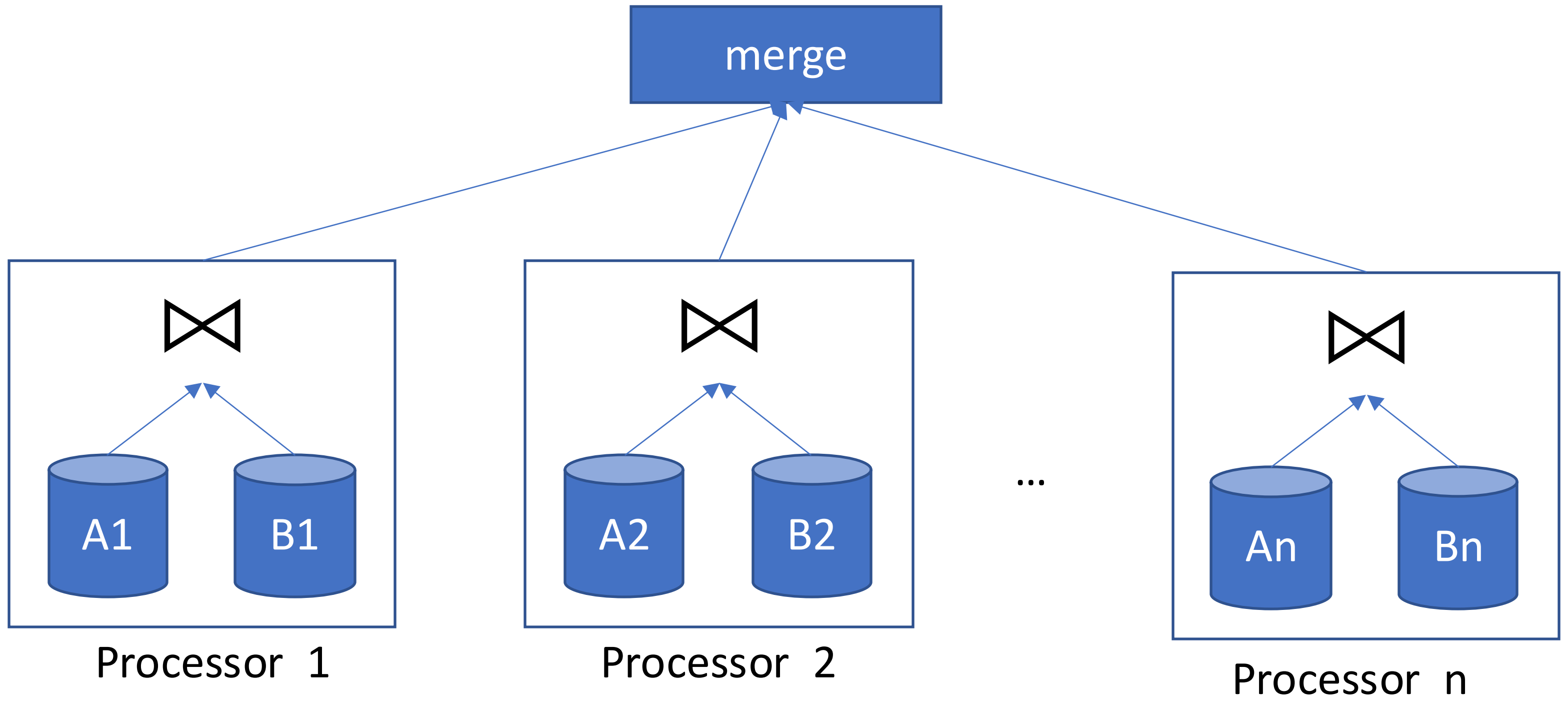
- **SELECT**
  - Trivial to “push down” to each worker
  - Depending on partitioning attribute, may be able to skip some partitions
- **PROJECT**
  - Assuming all columns are on each node, nothing to be done
- **JOIN**
  - Depending on data partitioning, may be able to process partitions individually and then merge, or may need to repartition
- **AGGREGATE**
  - Partially aggregate data at each node, merge final result

Join Strategies

- If tables are partitioned on same attribute, just run local joins
  - Also, if one table is replicated, no need to join
- Otherwise, several options:
  1. Collect all tables at one node
     - Inferior except in extreme cases, i.e., very small tables
  2. Re-partition one or both tables – “shuffle join”
     - Depending on initial partitioning
  3. Replicate (smaller) table on all nodes

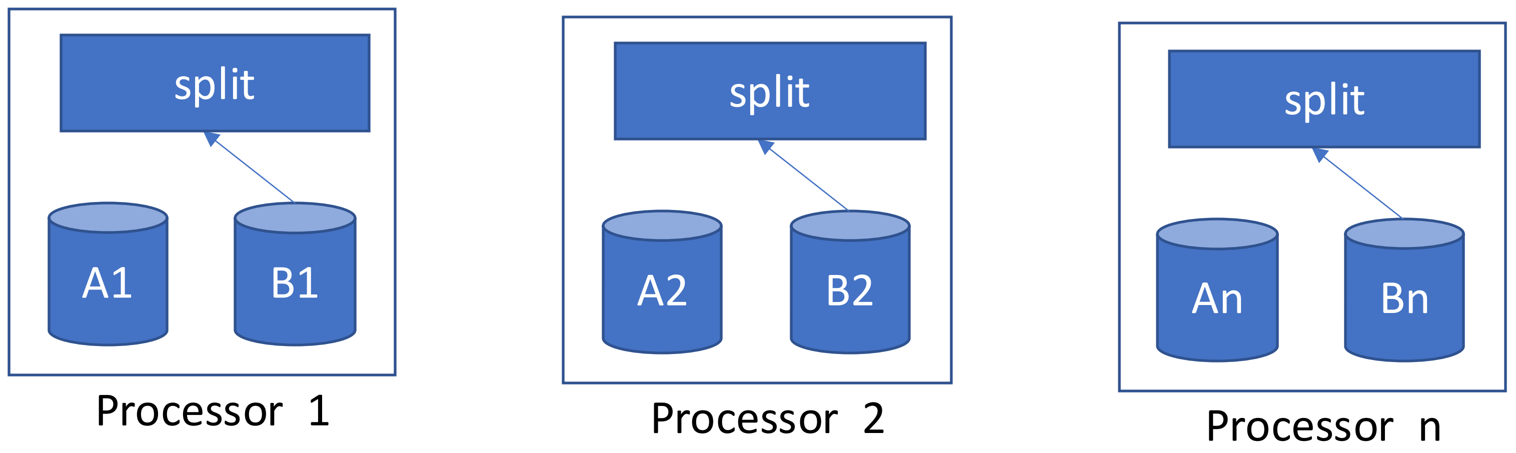
Table Pre-Partitioned on Join Attribute

- Suppose we have hashed A on a, using hash function F to get F(A.a) → 1..n (n = # machines)
- Also hash B on b using *same* F
- Query: SELECT * FROM A,B WHERE A.a = B.b



Repartitioning Example – "Shuffle Join"

- Suppose A pre-partitioned on a, but B needs to be repartitioned



Repartitioning Example

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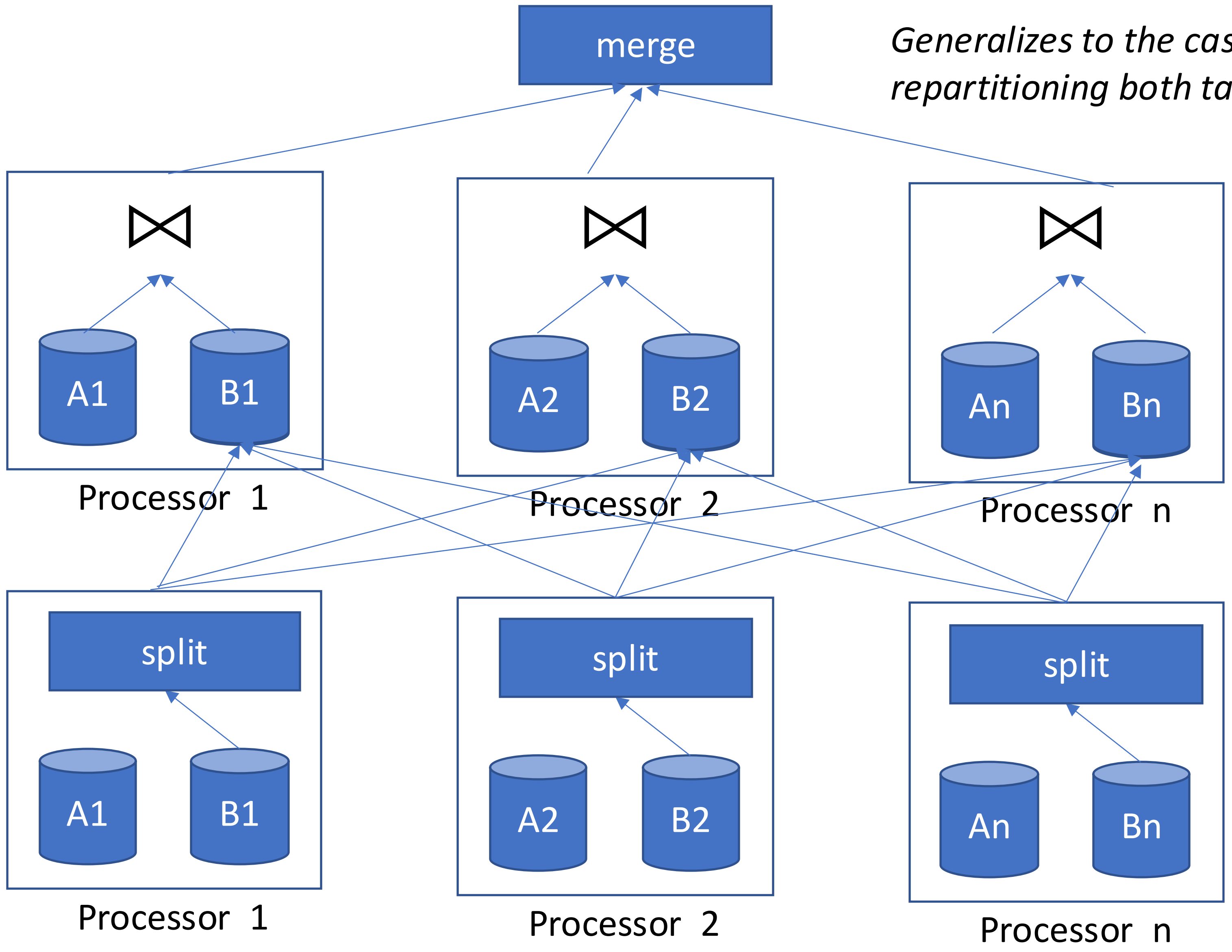
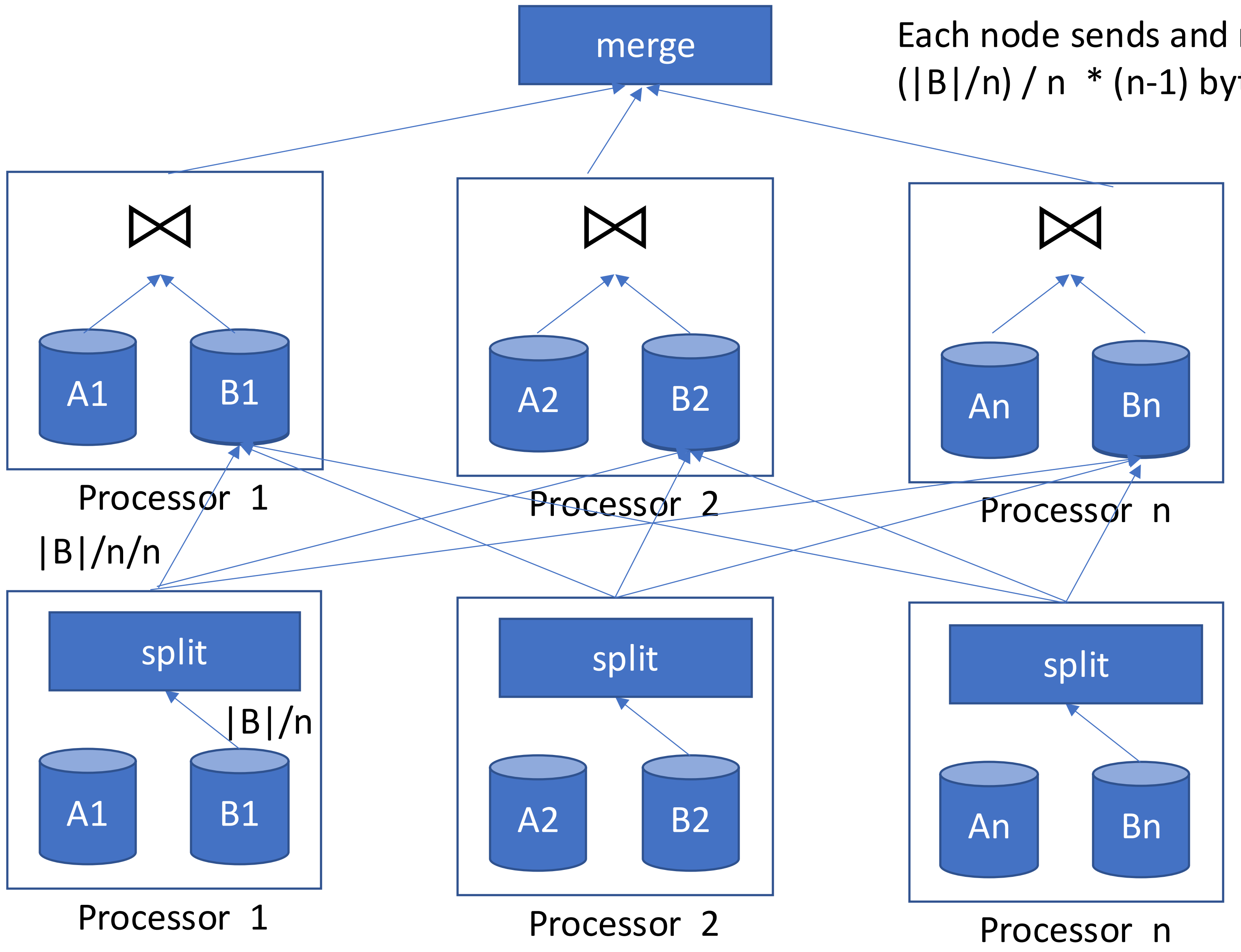


Generalizes to the case of repartitioning both tables

Repartitioning Example

- Suppose A pre-partitioned on a, but B needs to be repartitioned



Each node sends and receives (|B|/n) / n * (n-1) bytes

Each partition is |B| / n records
Repartitioning splits it into n new chunks, each node sends n-1 of them

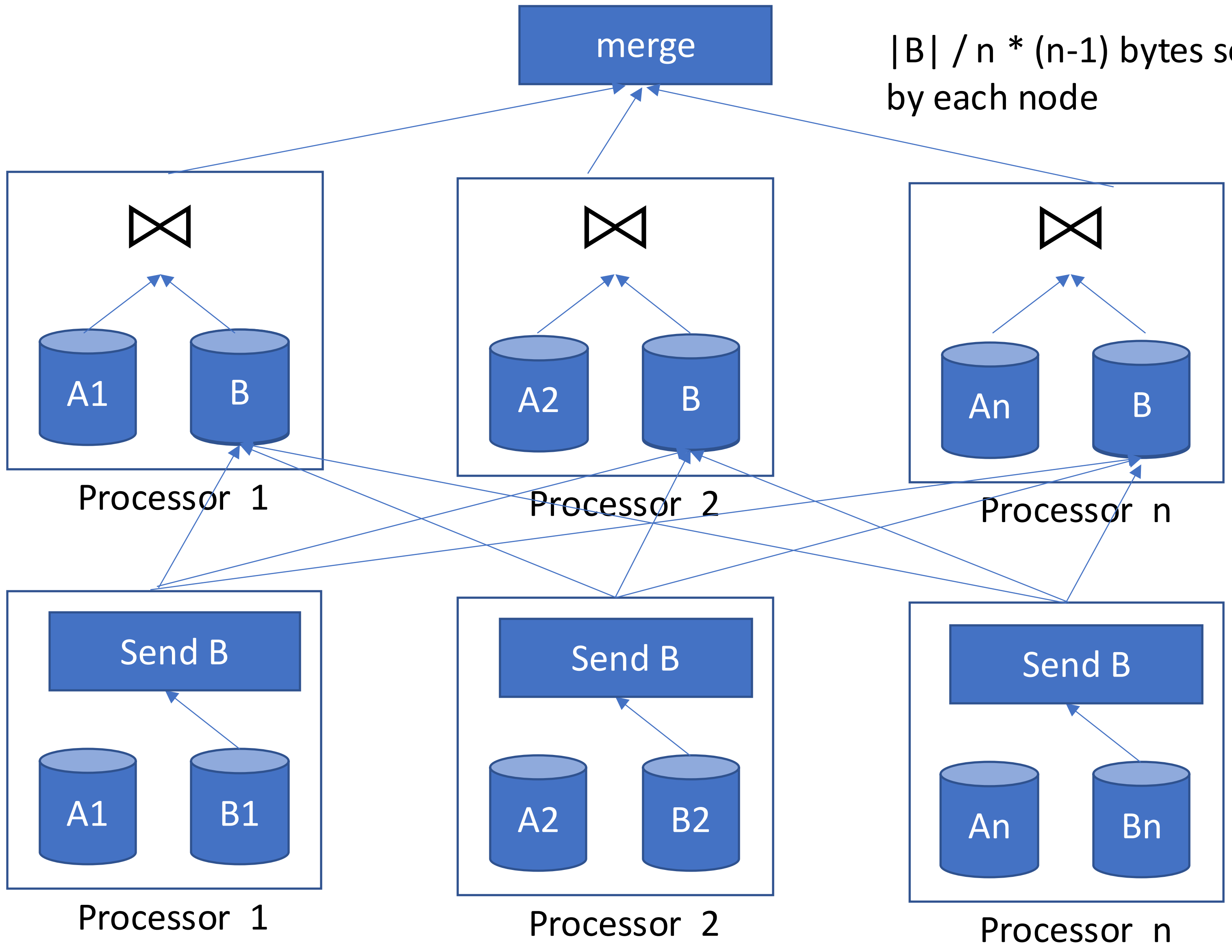
Repartitioning Both Tables

- Suppose both tables, A and B, need to be repartitioned
- Each node sends and receives

$$(|A|/n)/n * (n-1) + (|B|/n)/n * (n-1) \text{ bytes}$$

Replication Example

- Suppose we replicate B to all nodes



Replication vs Repartioning

- Replication requires each node to send smaller table to all other nodes
  - (|T| / n) * (n-1) bytes sent by each node
  - vs ((|T| / n) / n) * (n-1) to repartition one table
- When would replication be preferred over repartitioning for joins?
  - If size of smaller table < data sent to repartition one or both tables
  - Should also account for cost of join: will be higher with replicated table
- Example: |B| = 1 MB, |A|=100 MB, n=3
- Need to repartition A (B distributed on join attr)
  - Data to repartition A is |A|/3 / 3 * 2 = 22.2 MB per node
    - Join .33 MB to 33 MB
  - Data to broadcast B is |B| = 1/3 * 2 = .66 MB
    - Join 1 MB to 33 MB

Additional Options for Joins

- Pre-replicated small tables
    - If space permits, can be a good option

- ”Semi-join”
    - send list of join attribute values in each partition of B to A,
    - then send list of matching tuples from A to B,
    - then compute join at B
- Good for selective joins of wide tables
    - Pre-filters A with join values that actually occur in B, rather than sending all of B

ple

A	B	C	D	E
4	d	e	h	i
3	z	a	f	g

A	B	C	D	E
1	x	y	J	k

T1
P1

1	**x**	**y**
3	z	a

Node 1

T1
P2

A	B	C
2	b	c
4	**d**	**e**

Node 2

T2
P1

A	D	E
3	f	g
4	h	i

T2
P2

A	D	E
1	j	k
5	l	m

<u>Total cost:</u>

Each nodes sends & receives

$(|\text{join col}| \ / \ n) \ * (n-1)$

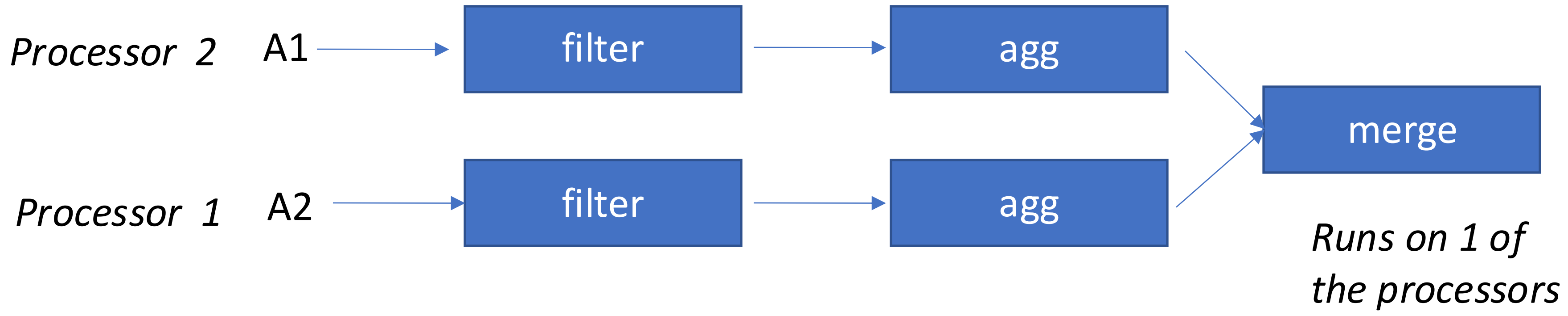
+

$(f * |A| \ / \ n) \ * (n-1)$

Where f is join selectivity

(Like cost of replication, but only for 1 column +filtered |A|)

Aggregation



In general, each node will have data for the same groups

So merge will need to combine groups, e.g.:

MAX (MAX1, MAX2)
SUM (SUM1, SUM2)

What about average?
Maintain SUMs and COUNTs, combine in merge step

Generalized Parallel Aggregates

- Express aggregates as 3 functions:
  - INIT – create partial aggregate value
  - MERGE – combine 2 partial aggregates
  - FINAL – compute final aggregate

  - E.g., AVG:
    - INIT(tuple) → (SUM=tuple.value, COUNT=1)
    - MERGE (a1, a2) → (SUM=a1.SUM + a2.SUM, COUNT=a1.count+a2.count)
    - FINAL(a) → a.SUM/a.COUNT

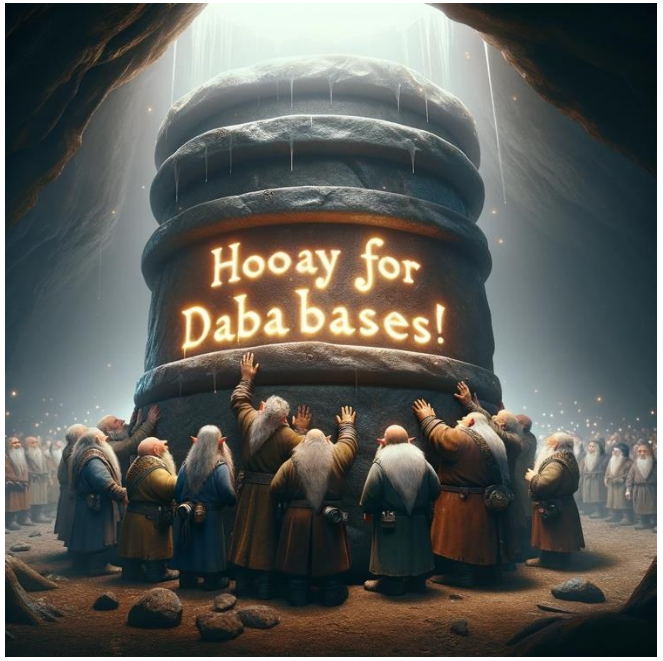
What does MERGE do?

- For aggregate queries, receives partial aggregates from each processor, MERGEs and FINALizes them

- For non-aggregates, just UNIONs results

DB Parallel Processing vs General Parallelism

- Shared nothing partitioned parallelism is the dominant approach
- Hooray for the relational model!
  - Apps don't change when you parallelize system (physical data independence!).
  - Can tune, scale system without changing applications!
  - Can partition records arbitrarily, w/o synchronization
- Essentially no synchronization except setup & teardown
  - No barriers, cache coherence, etc.
  - DB transactions work fine in parallel



Rest of the lecture:
Distributed Transactions!

Break

Distributed Transactions

- Suppose we have data on separate machines and want to run a transaction across them

- <u>Example 1</u>: reserve a rental car and an airline flight, and only commit if both are available.
- <u>Example 2</u>: transfer money from bank 1 to bank 2
- <u>Example 3</u>: add a friend to a social media graph, where user 1 is on Asia server and user 2 is on US server

Problem with Distributed Transactions

- Consider:

BEGIN
INSERT A → Machine 1
INSERT B → Machine 2
INSERT C → Machine 3
COMMIT

Problem: Machine 1 & 2 commit, Machine 3 crashes
What happens?

Goal: Atomicity

- If one machine crashes, system should still preserve atomicity

➔ Crashing machine should recover & commit

or

➔ All machines (including crashing one) should rollback

In single-node system, a transaction is committed the moment the commit record goes to disk

In multi-node system, can’t ensure commit record is all-or-nothing across all nodes!

Two-Phase Commit

- Key Idea: Add a new state, “PREPARED” to transactions

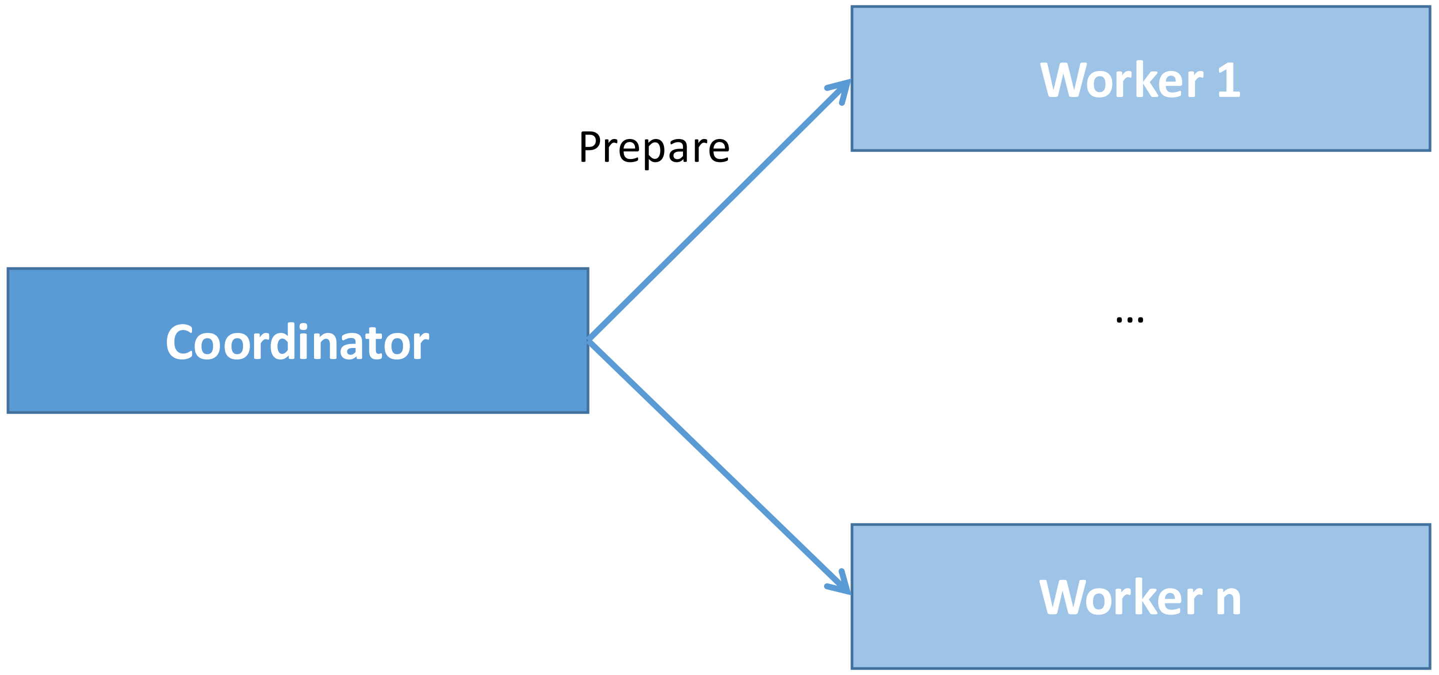
- Indicates that a node has done the work for a transaction, and the decision to COMMIT/ABORT will be done by a *coordinator*

- Once prepared, a node will not COMMIT or ABORT on its own

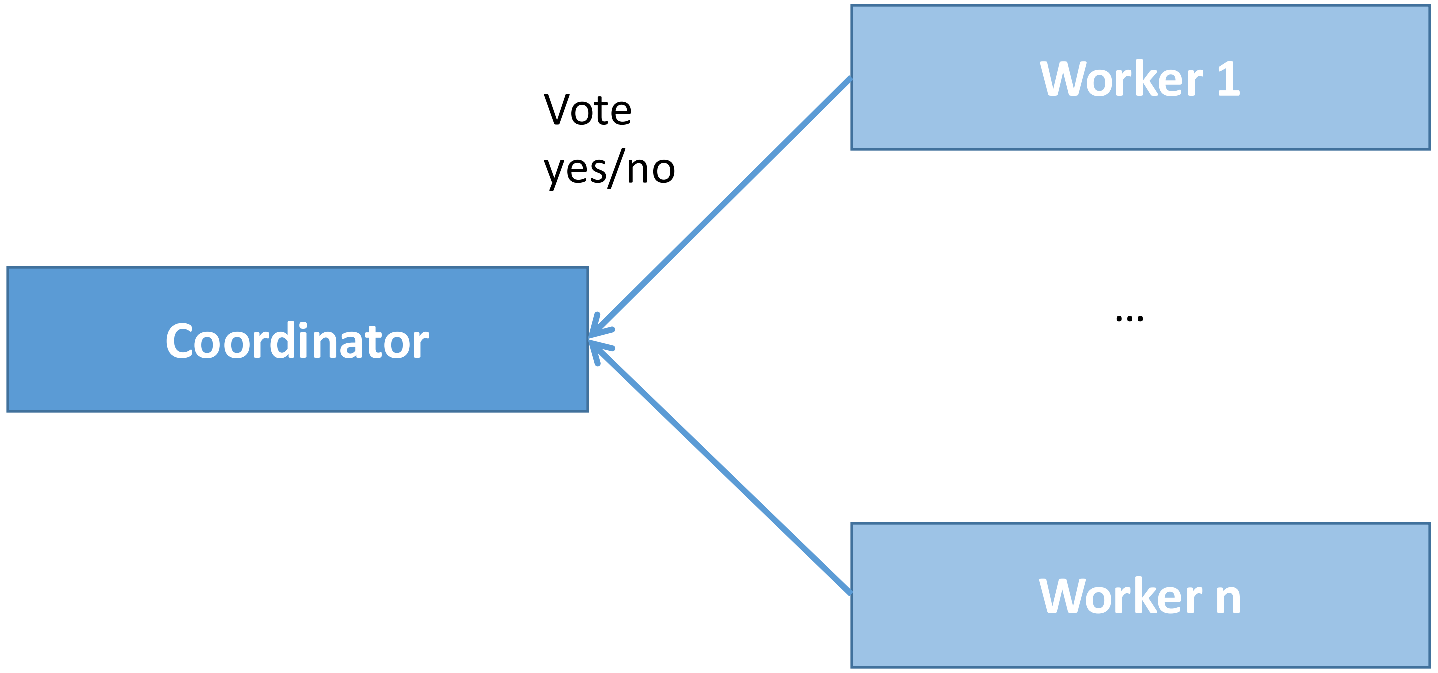
➔”Prepared” state must survive crashes

(Postgres Demo)

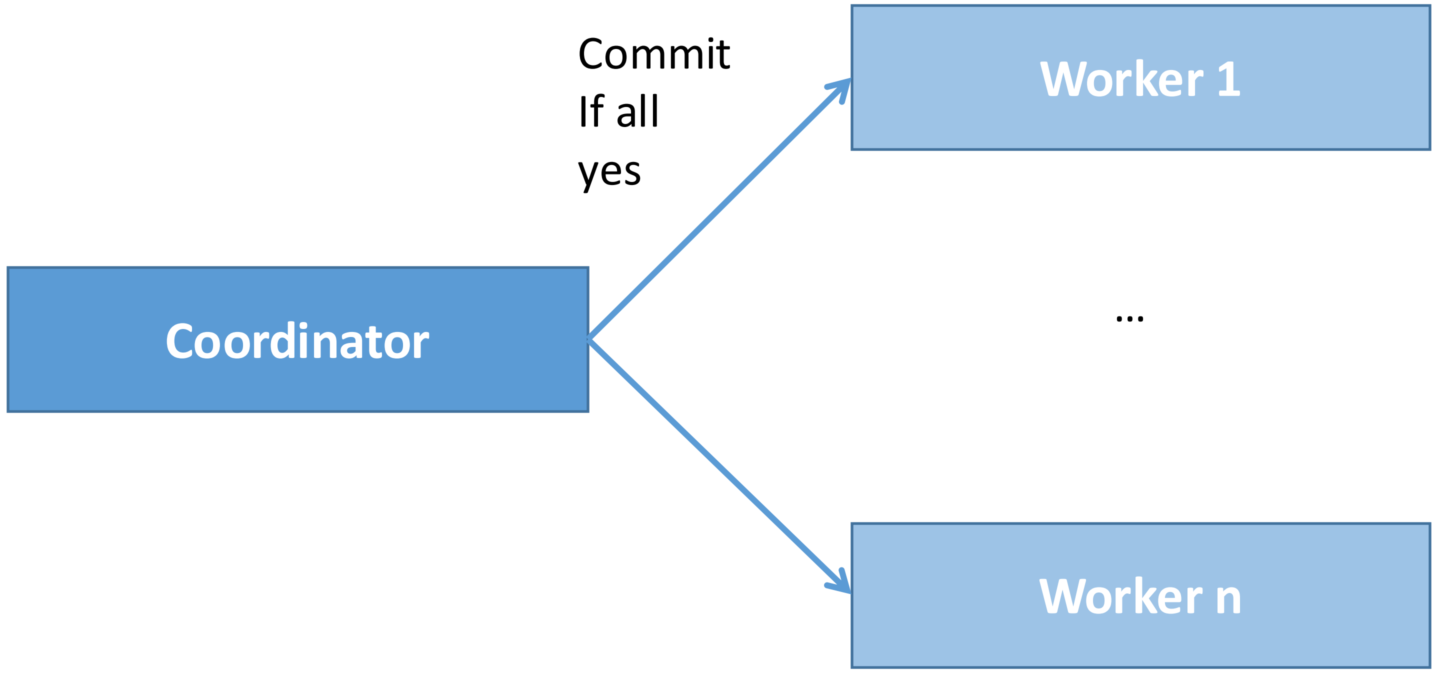
2PC Architecture



2PC Architecture



2PC Architecture



Two-Phase Coordinator Overview

This commits the transaction

1. Log start of transaction
2. Execute transaction on *worker* nodes
3. PREPARE each worker
4. Once workers are all prepared, log transaction commit
5. Commit each worker
6. Log DONE, so we know all transactions are done

(If one of the workers fails to prepare, abort each worker)

What If Coordinator Crashes

- Log tells us which transactions were running
- If before Coordinator COMMIT, all workers should abort
  - Some may have prepared, some may not
  - (Workers may be asked to abort unprepared transactions)
- If after Coordinator COMMIT, but not DONE all workers should commit
  - Some may have committed, some may not
  - (Workers must be asked to commit transactions again)

What Happens in Worker PREPARE?

- Because PREPAREd state is not committed, a worker must:
  - Hold locks until COMMIT or ABORT
  - Be able to COMMIT / ABORT even if it crashes
- Because PREPAREd state must survive a crash, a worker must
  - Log that it is prepared (before acknowledging the prepare to coord)
  - Recover back into the PREPAREd state (re-acquiring locks!)
- Requires logging locked objects, and forcing log to disk before acknowledging PREPARE

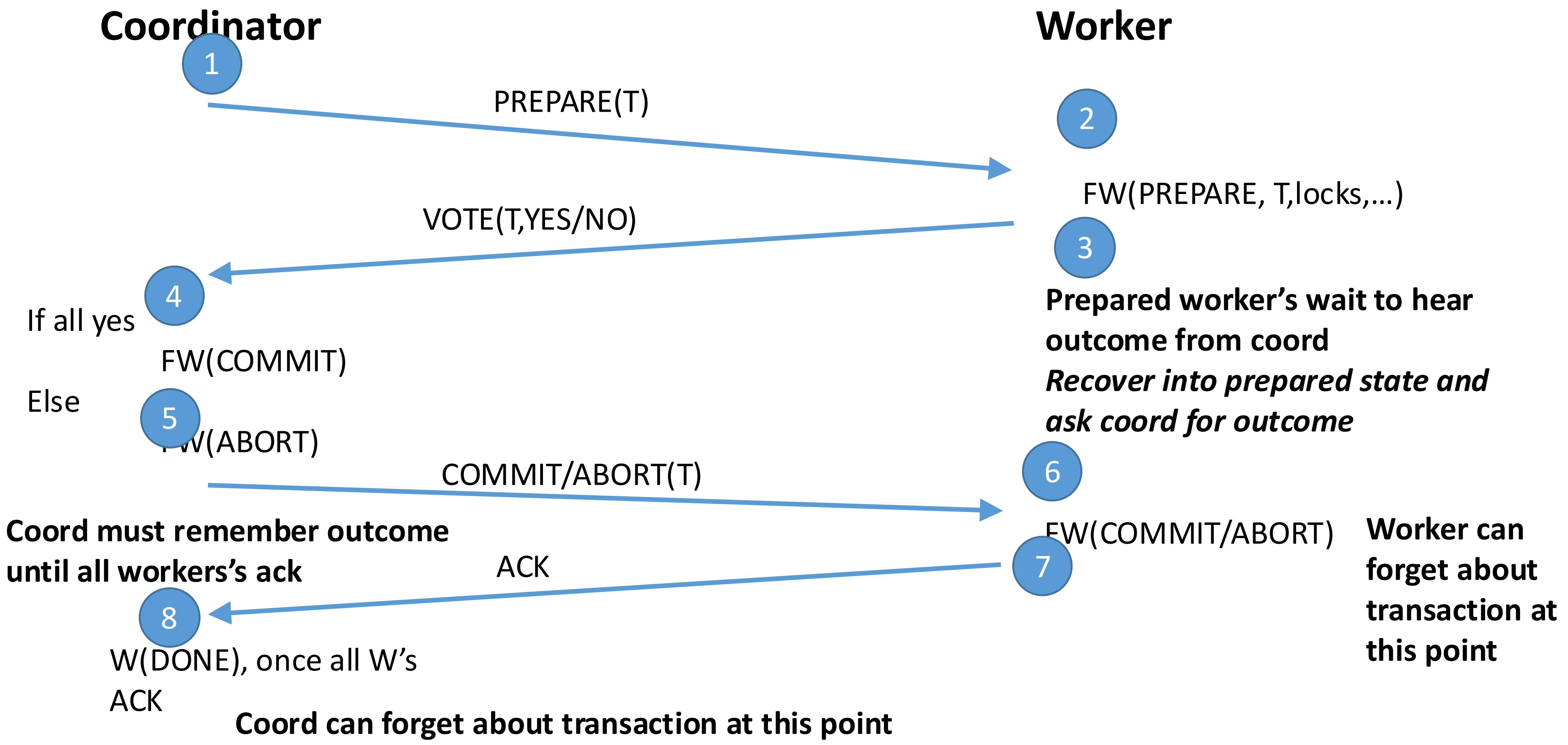
Worker Recovery Process

- Each worker has a *recovery process* that keeps track of the outcome of transactions running on the site
- If a site is prepared and crashes, it needs to ask coordinator about the outcome of the transaction on recovery

- This is not handled in our pseudocode, or Postgres
- Would require a separate monitor for each DB

Two-phase commit protocol

FW = Force Write



Prepared worker’s wait to hear outcome from coord

Recover into prepared state and ask coord for outcome

Coord must remember outcome until all workers’s ack

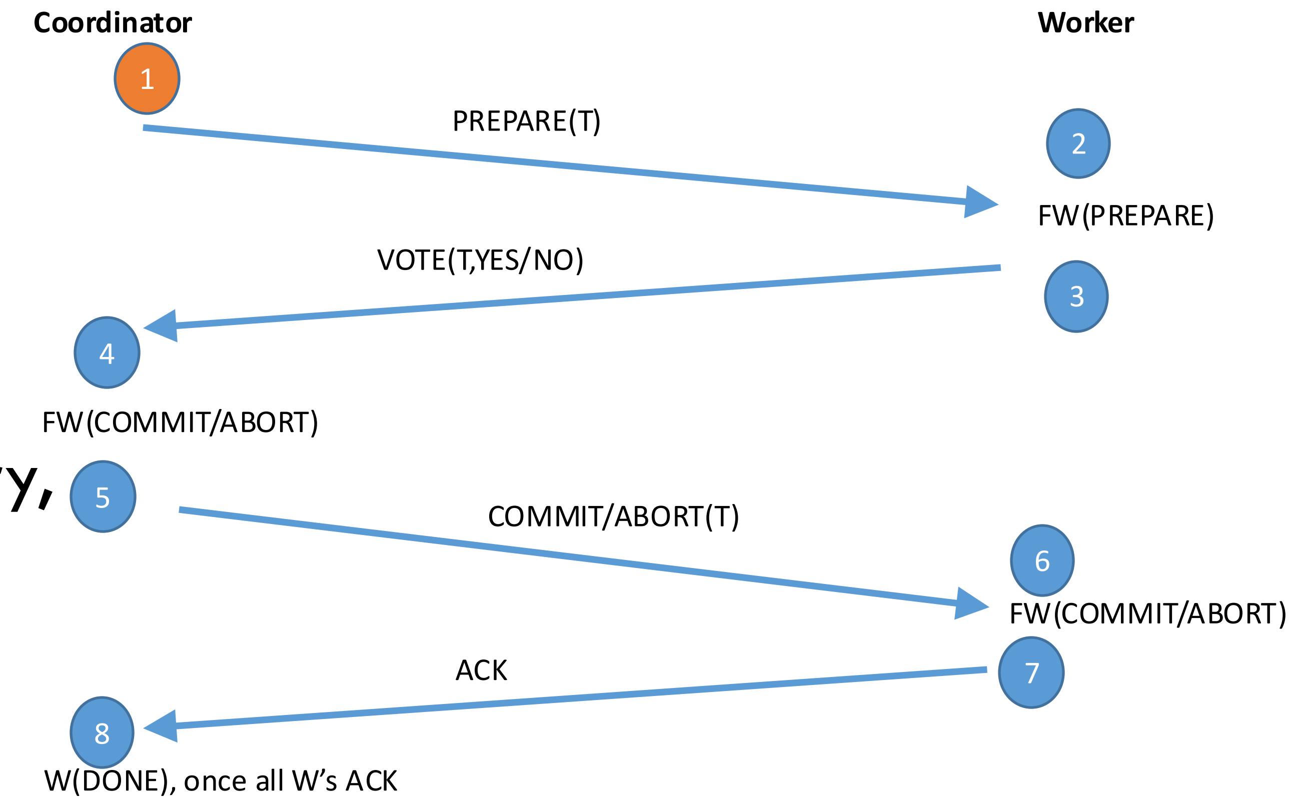
Worker can forget about transaction at this point

Coord can forget about transaction at this point

Failure Cases

(1) Coordinator crashes before sending PREPARE

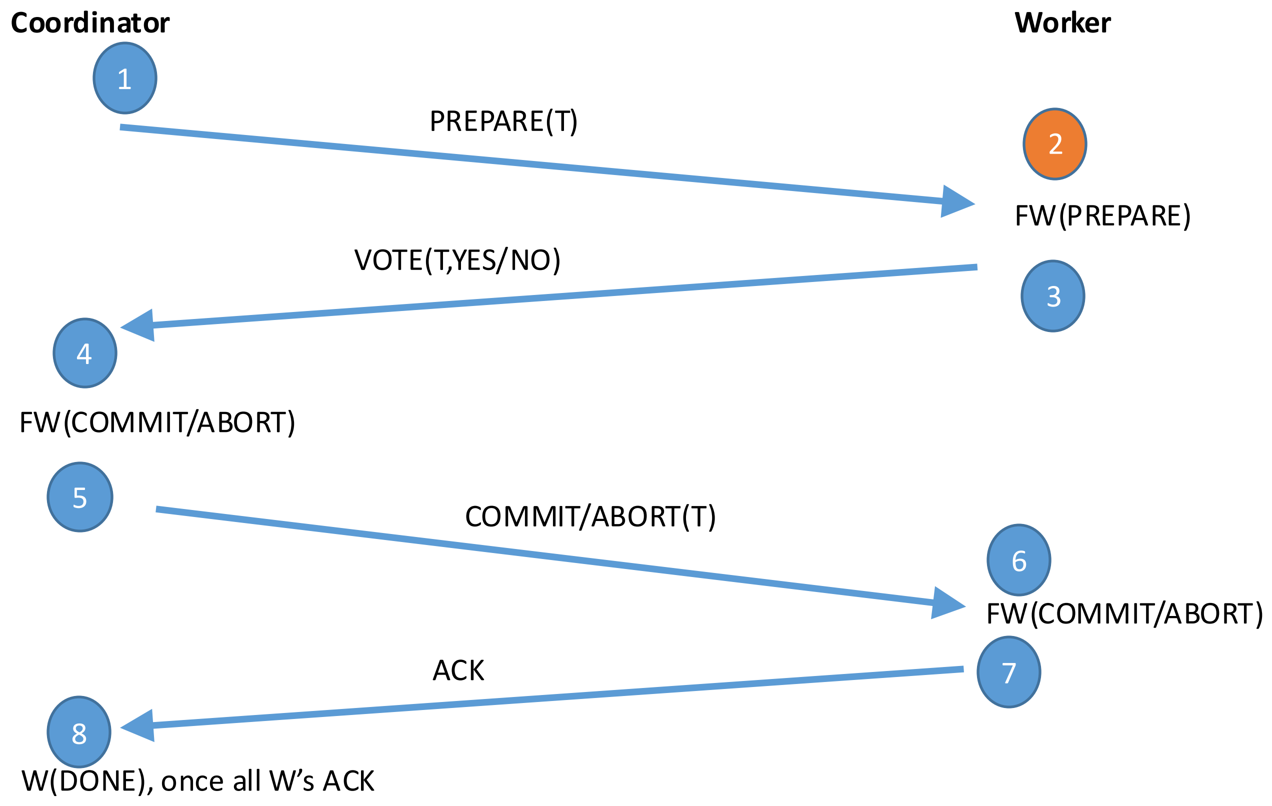
- Coord – will recover, abort transaction just as in normal recovery, discarding all state
- Worker – can safely abort;
  - Add *recovery process* that polls coordinator for status of outstanding txns
  - Coord, which has no record of txn, will tell worker to abort



Failure Cases

(2) Worker crashes before receiving PREPARE

- Coord – will never hear reply, will abort
- Worker – will recover, rollback txn during recovery



Failure Cases

(3) Worker crashes after PREPARE

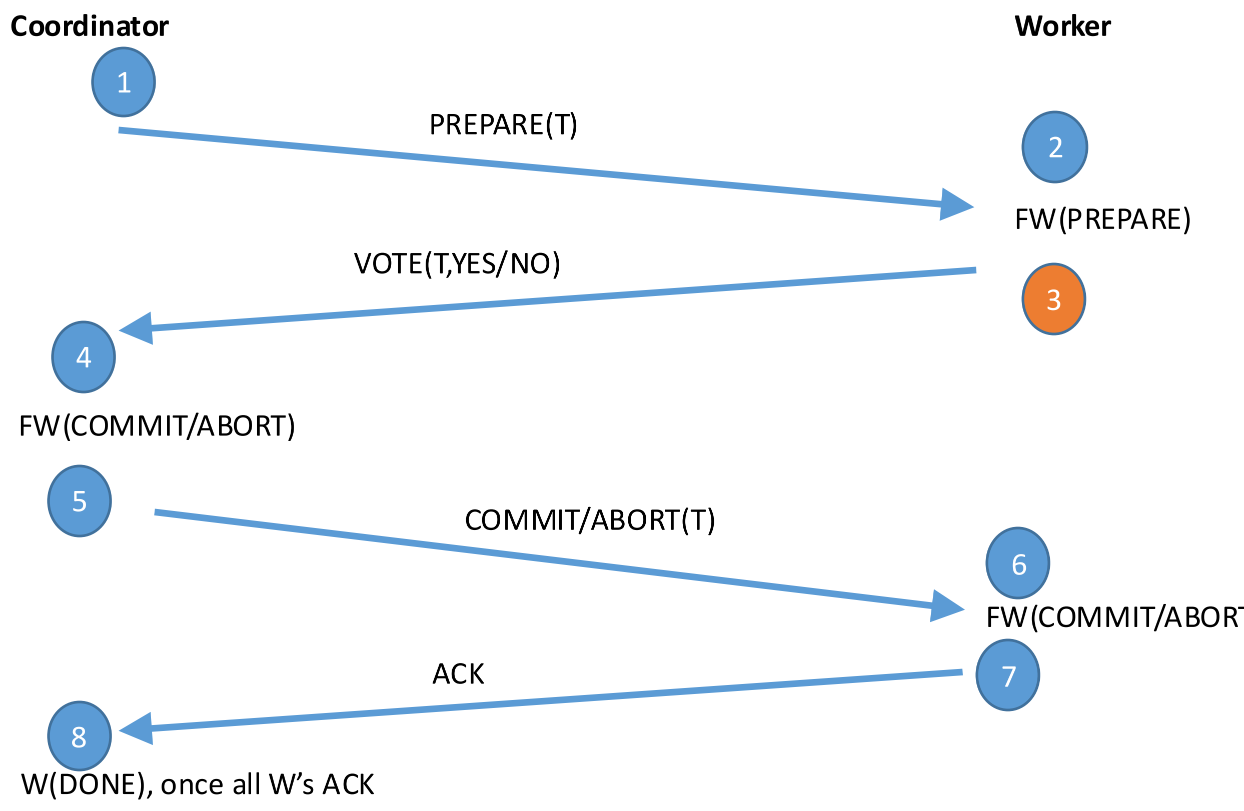
Must determine outcome from coord:

Two cases

(a) It already sent its vote, and coord is waiting for an ack -- thus, worker can learn fate by contacting coord

(b) It didn't send its vote, in which case coord may or may not have timed out.

- If it has not timed out, it can vote.
- If it has timed out, it *must* have aborted, and will tell the worker this.

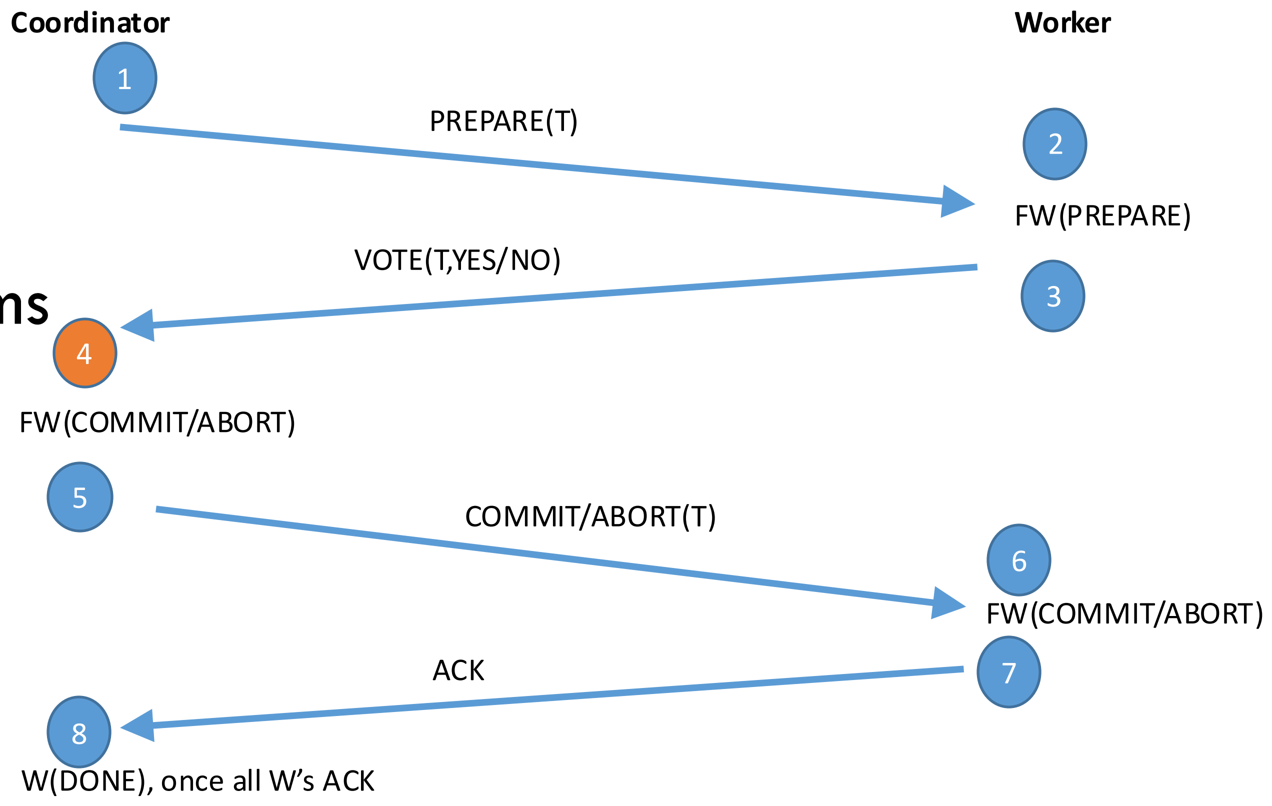


Failure Cases

(4) Coordinator crashes before receiving all votes

Coord aborts during recovery, informs workers

Note that workers who have prepared must wait for coordinator to restart to hear outcome

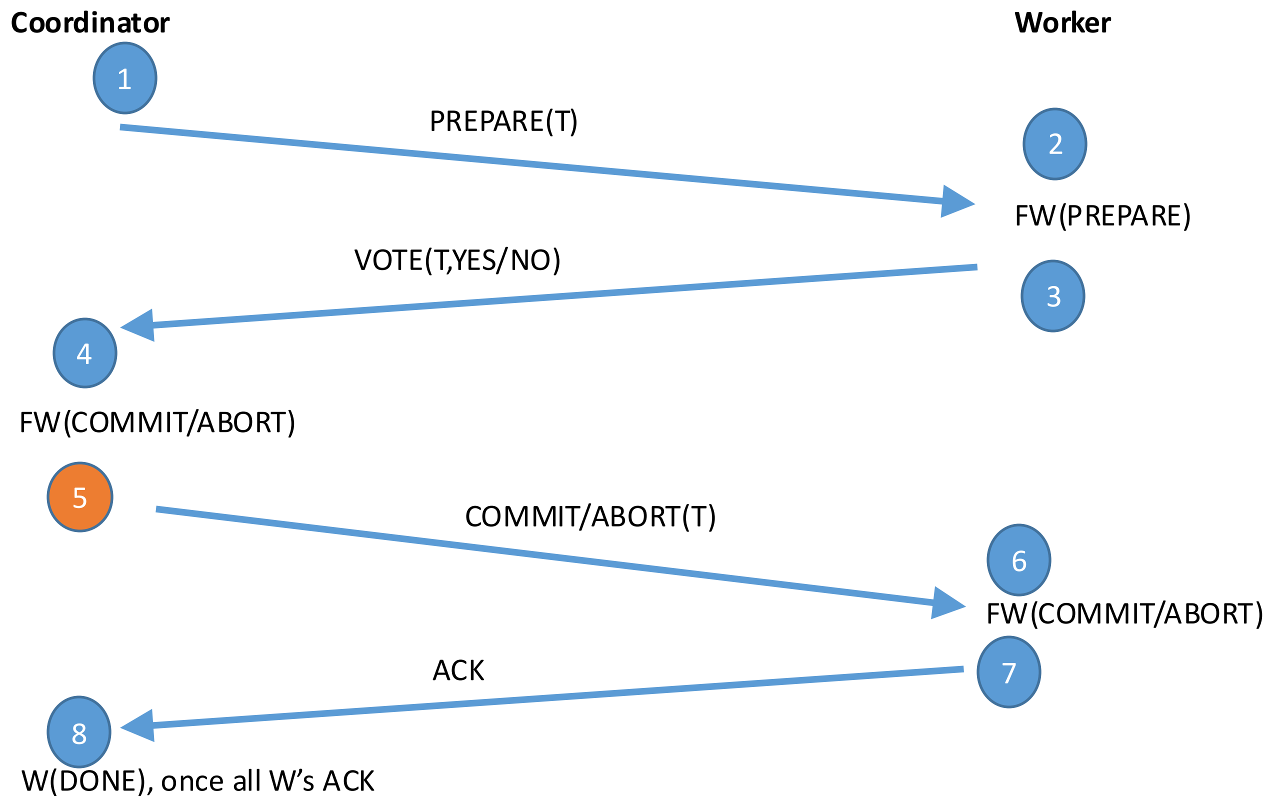


Failure Cases

(5) Coordinator crashes after writing COMMIT

No DONE record; coordinator sends commits to all workers

Workers must wait to hear outcome

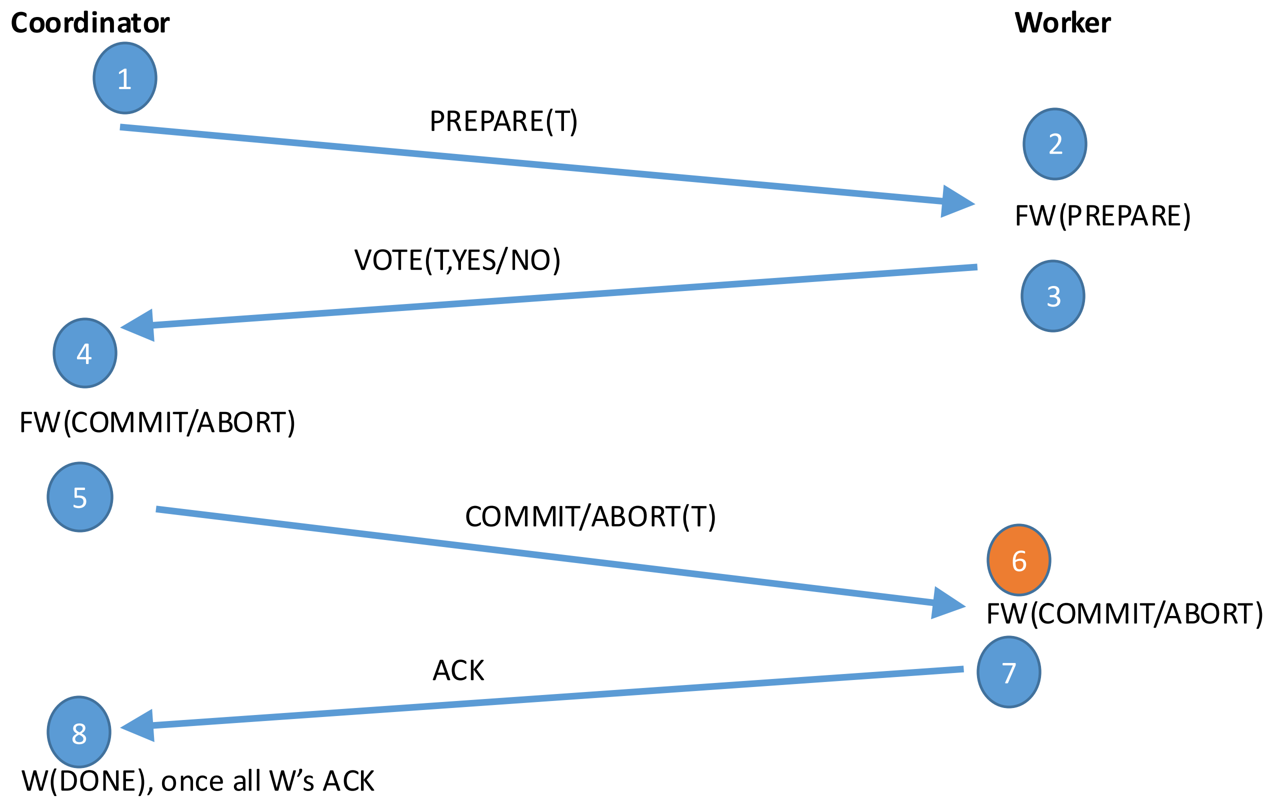


Failure Cases

(6) Worker crashes before receiving COMMIT / ABORT

Upon recovery, recovery process polls for outcome.

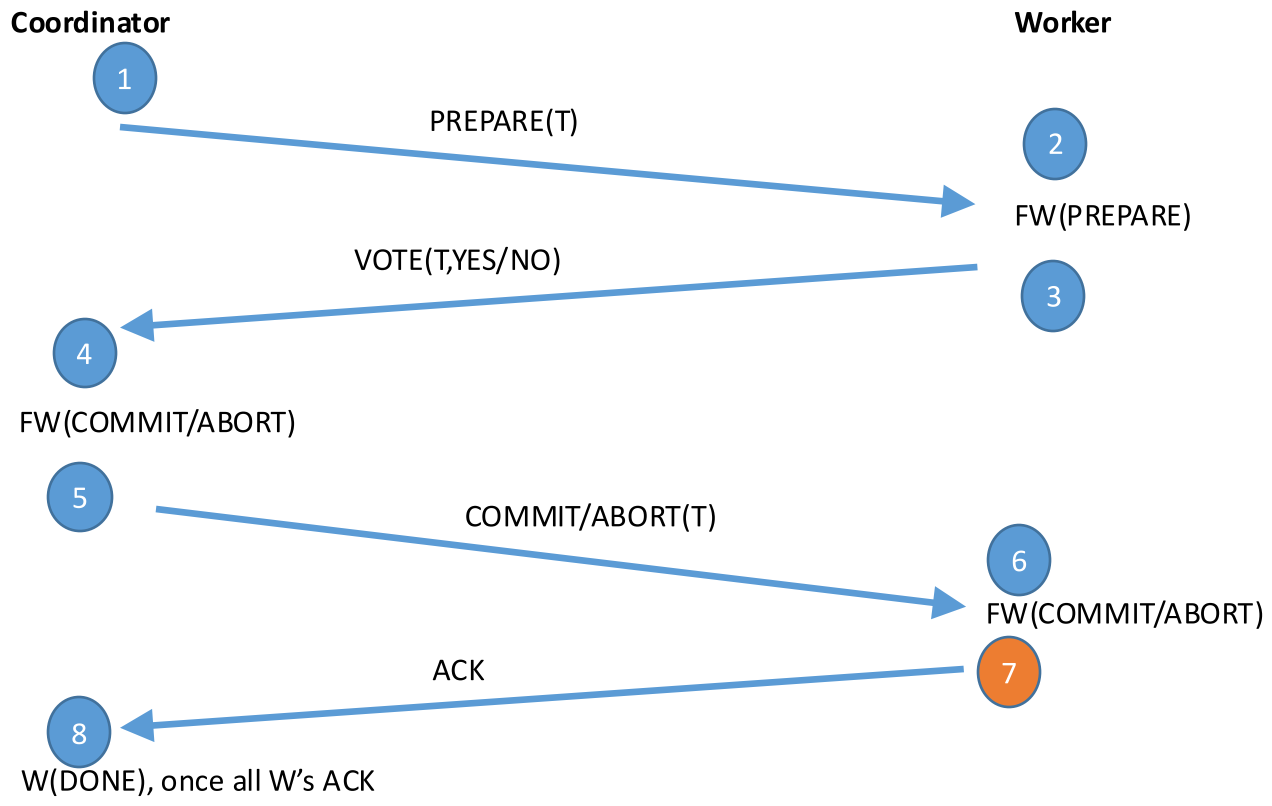
Since coordinator has not received ACK, it still knows state.



Failure Cases

(7) Worker crashed after writing COMMIT record, before ACKing.

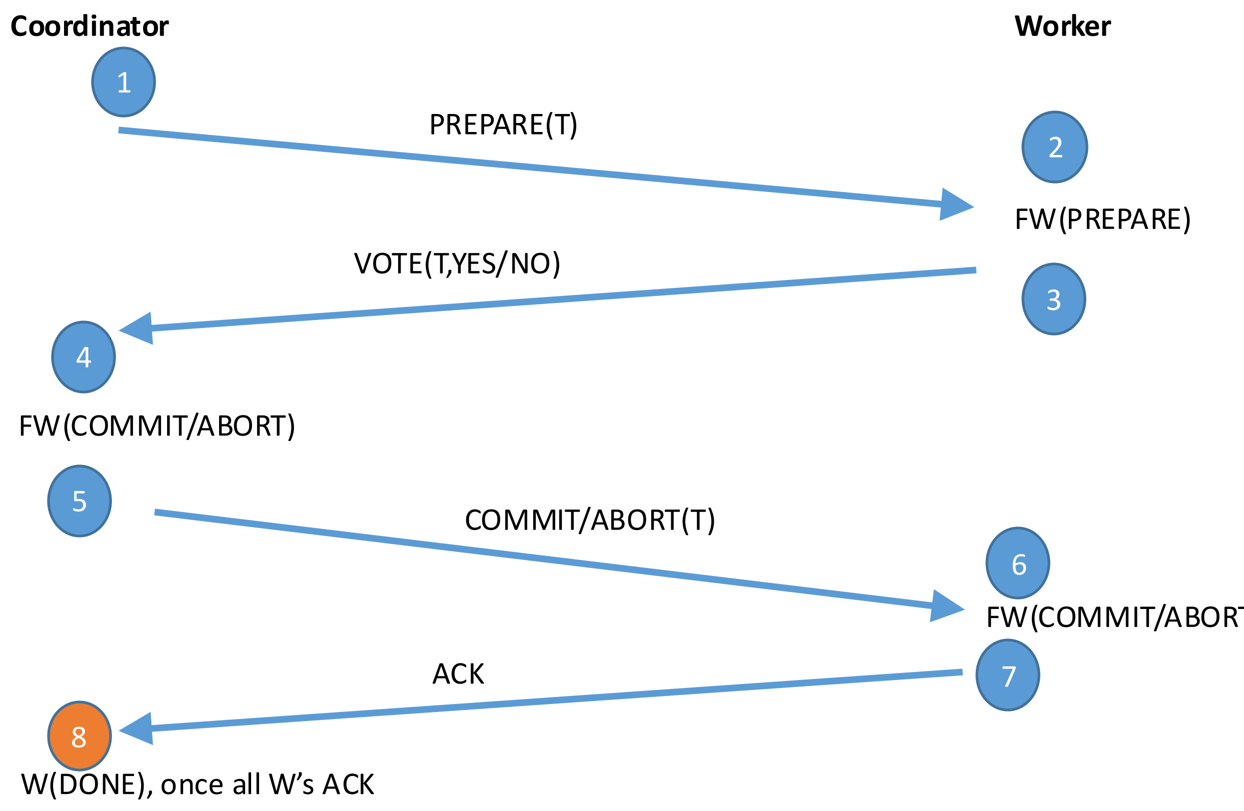
Worker will recover, transaction will be committed. Coordinator will periodically send a COMMIT message, which worker will ACK without writing any additional state.



Failure Cases

(8) COORD Crashed after receiving some ACKs.

COORD will send COMMIT/ABORT to all workers, who will ACK.



Read-only Workers

- If a worker is read-only (RO), it can send a "READ VOTE"
    - Doesn't need to write any log records
    - Can forget the transaction after it votes
- Coord doesn't need to send ABORT/COMMIT to RO workers
- If all workers are RO, no ABORT/COMMIT messages needed

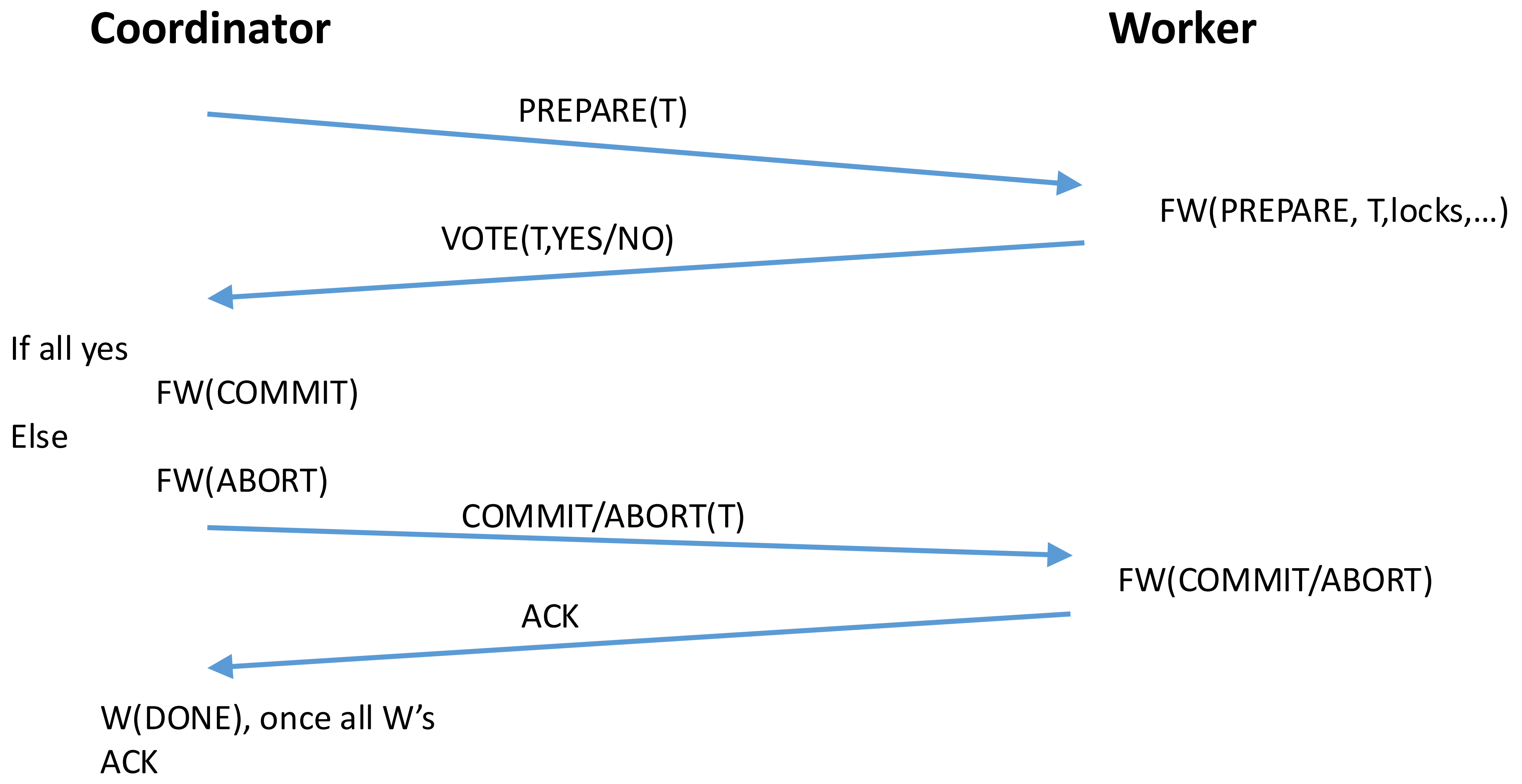
Two Variants

- **Presumed Abort** and **Presumed Commit**
- Avoid some logging when transactions abort / commit

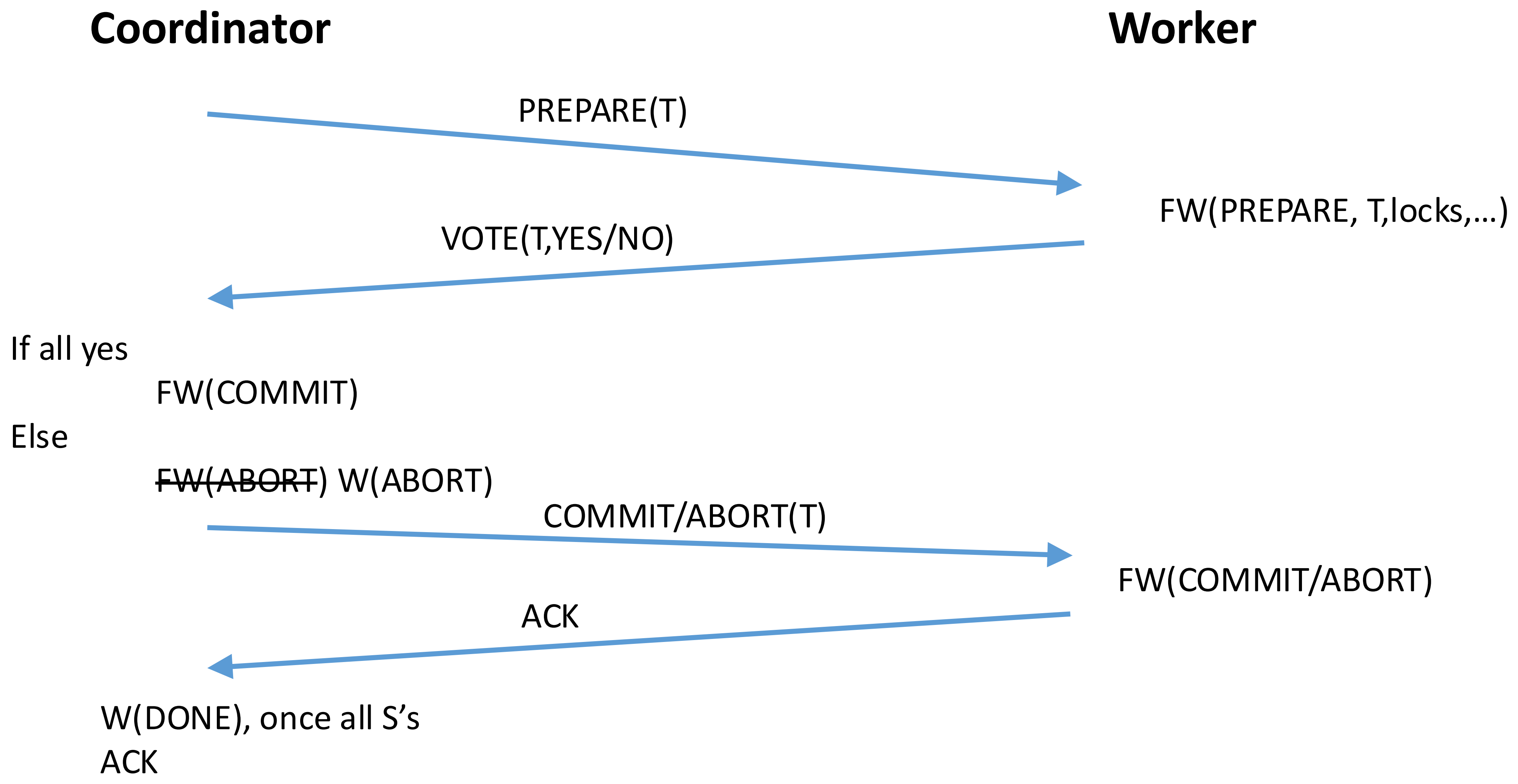
Presumed Abort

- Notice that in the existing protocol, if a recovery process contacts coordinator, and coordinator has no info about transactions, it replies “abort”
- Implies we do not need to force writes for aborting transactions
- Committing transactions are unchanged

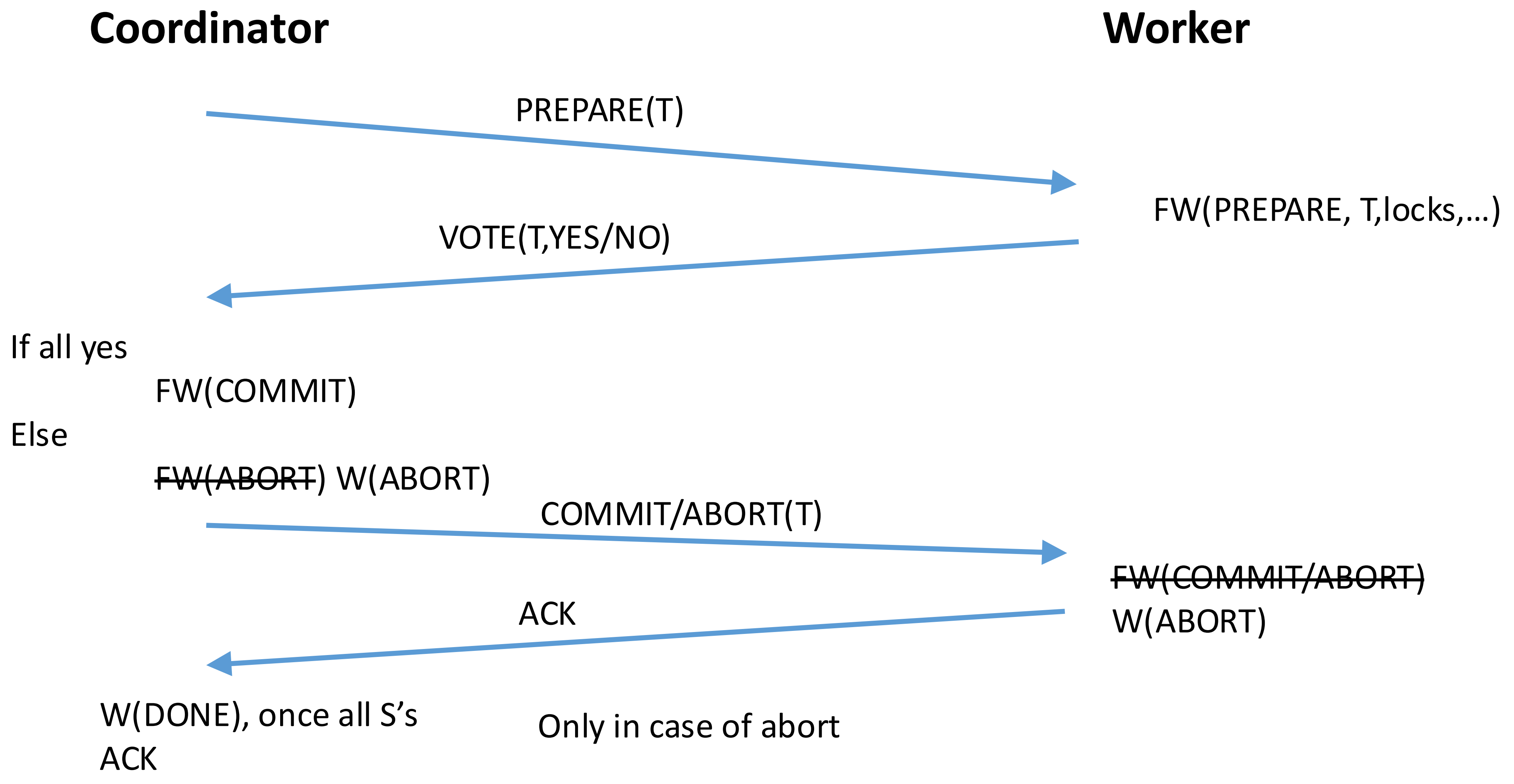
Presumed Abort – if transaction aborts



Presumed Abort – if transaction aborts



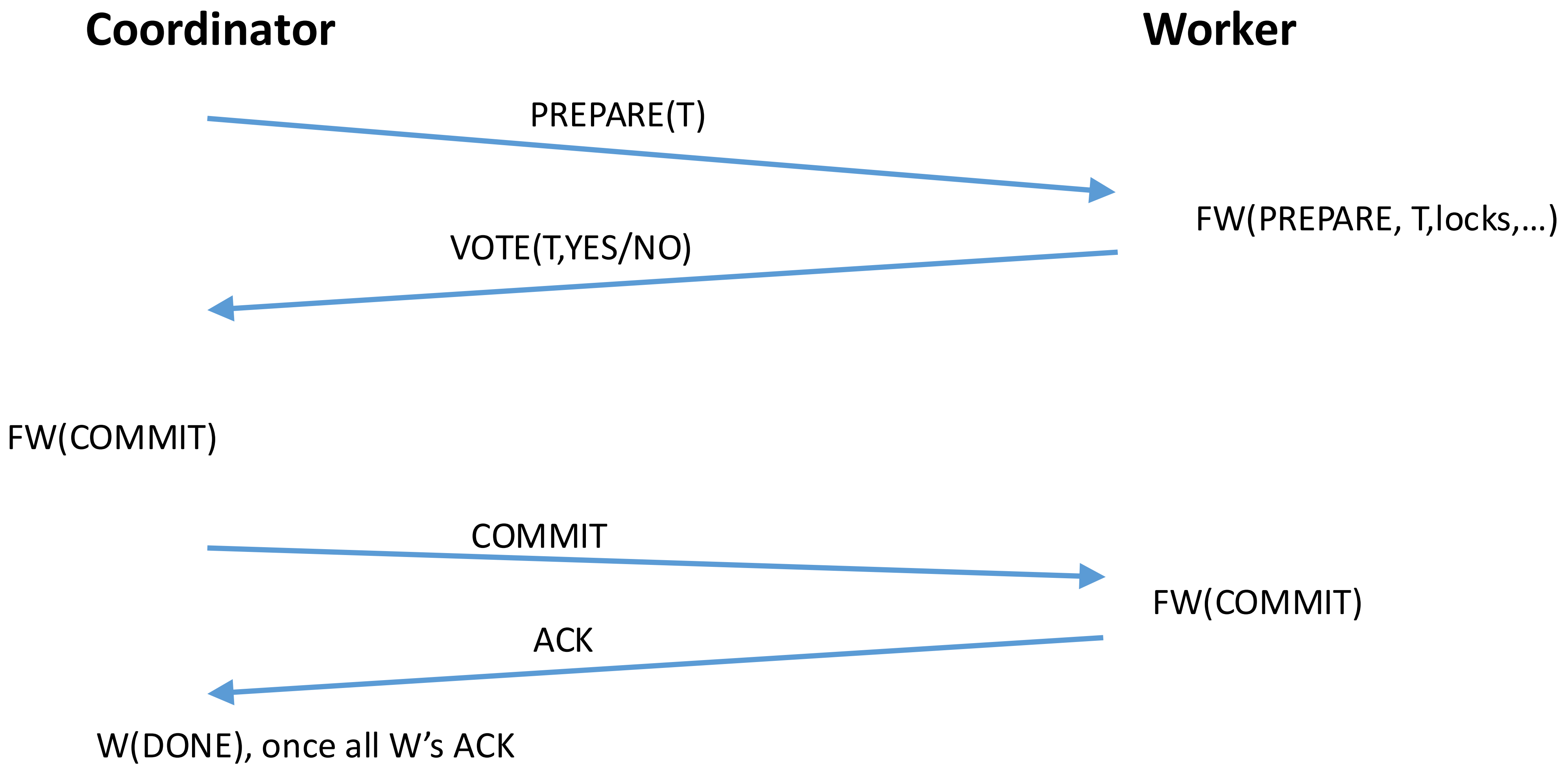
Presumed Abort – if transaction aborts



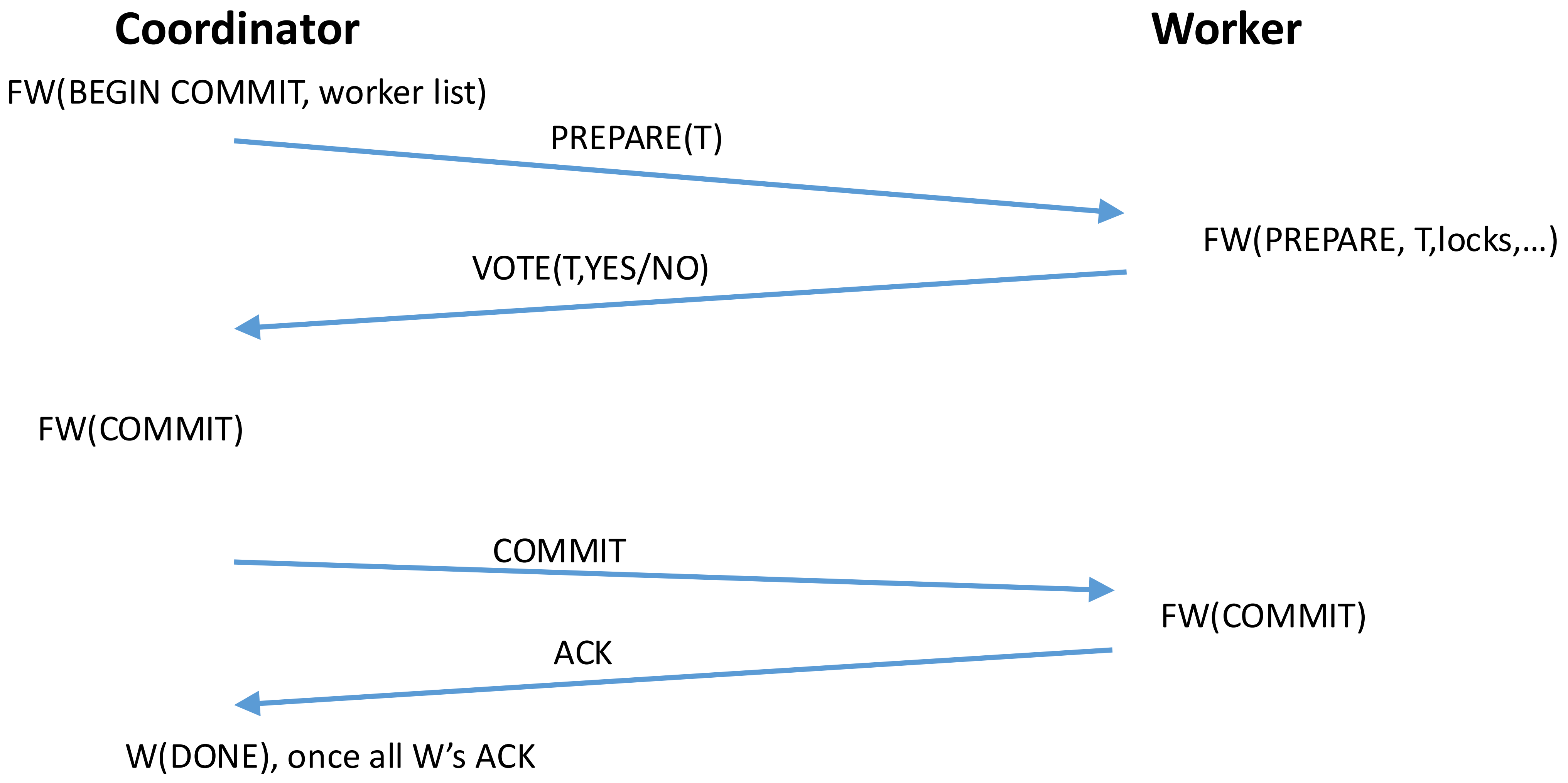
Presumed commit – if transaction commits

- Can’t just reply “COMMIT” in no information case
  - Suppose coord sends prepare messages, then crashes
  - Worker sends vote, doesn’t hear anything, re-requests
  - Eventually coord recovers, rolls back, and replies “COMMIT” (because it has no information about txn)
- Soln: prior to sending prepare, coord force writes an additional “BEGIN COMMIT” records with a list of all workers
  - If it crashes prior to writing COMMIT/ABORT, it can restart commit process, contact workers, collecting votes and sending outcomes
- Adds an additional write on coord, but allows worker COMMIT to be an async write

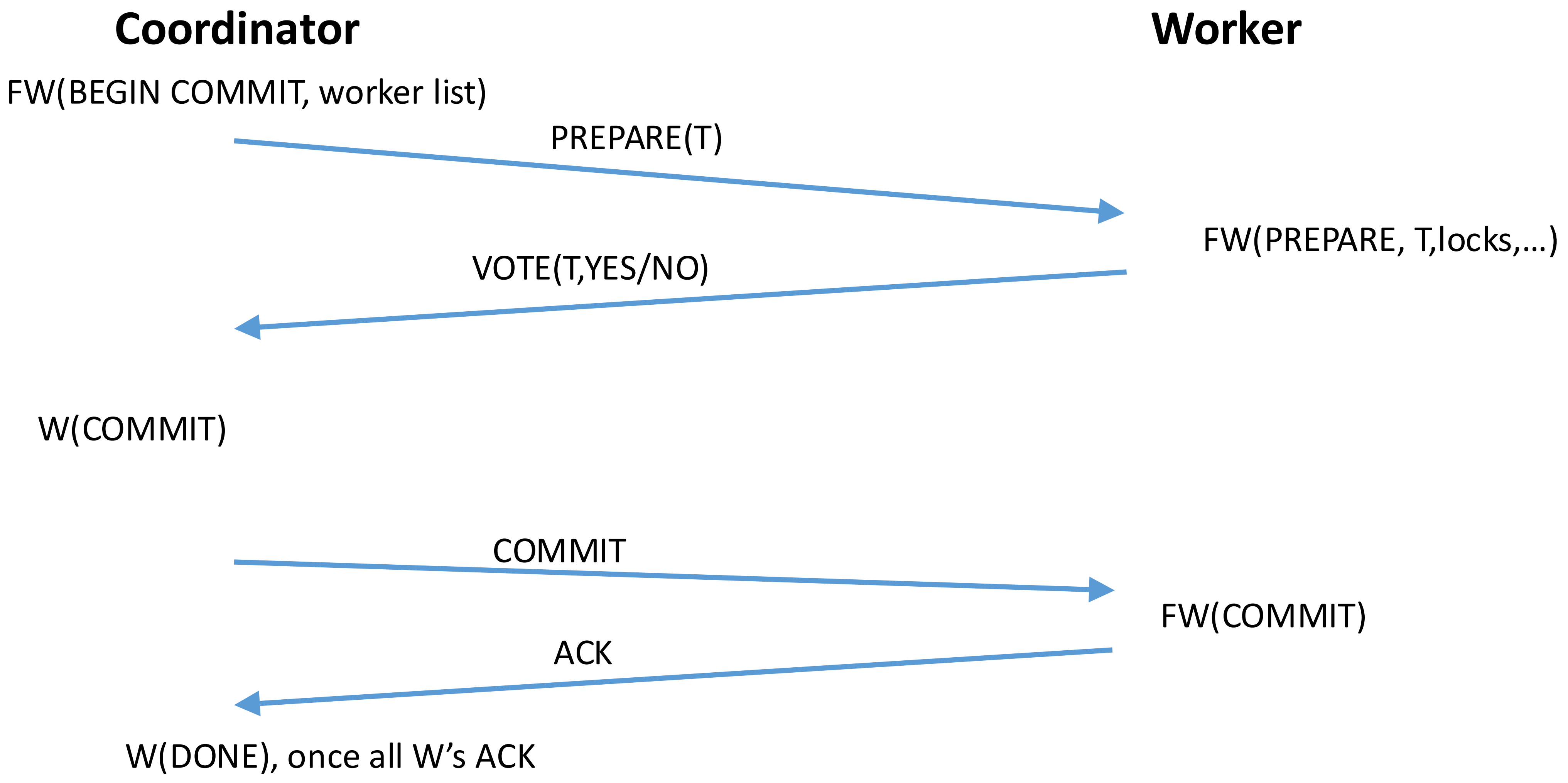
Presumed commit – if transaction commits



Presumed commit – if transaction commits



Presumed commit – if transaction commits



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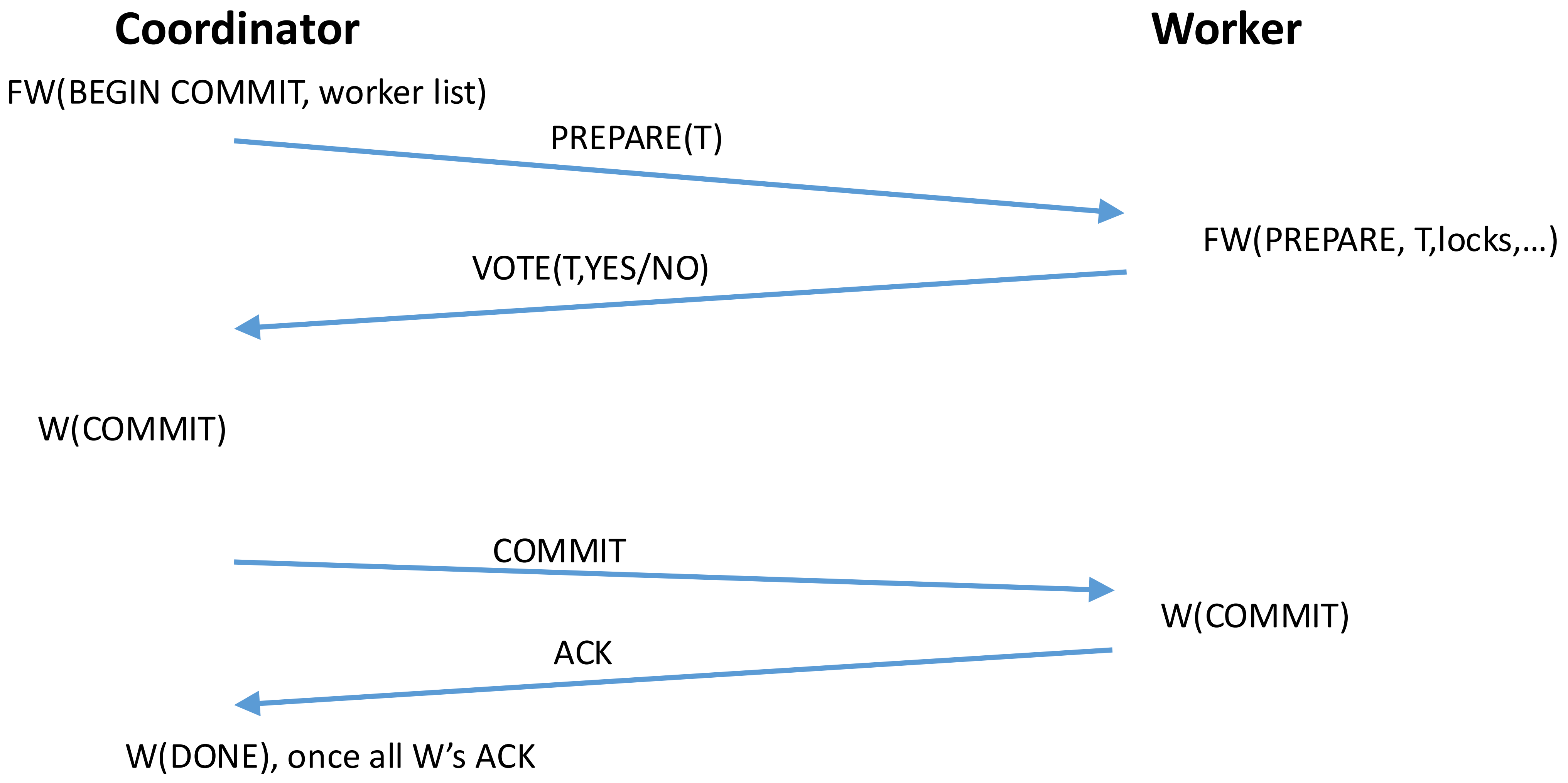
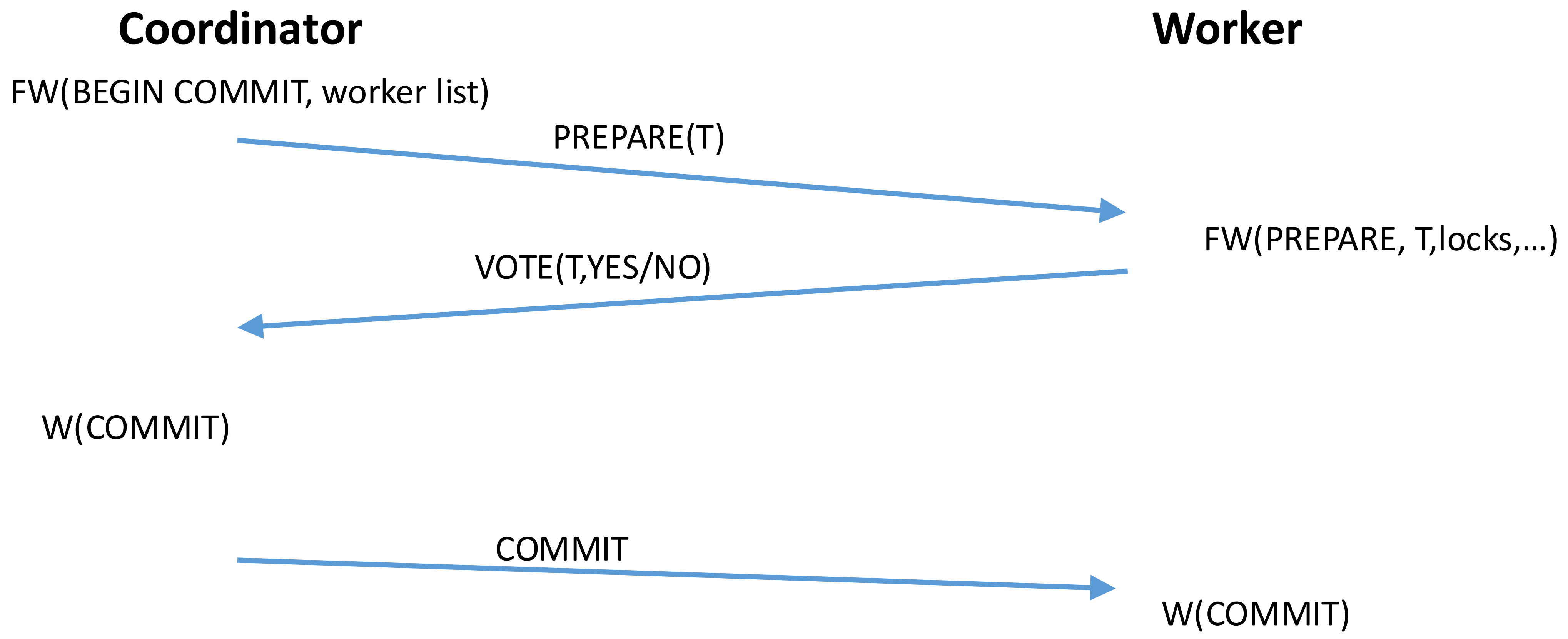


Presumed commit – if transaction commits



Abort case still retains all writes
of regular protocol

Summary: Write/Message Complexity

W = Write
F = Force Write
M = Message

Messages for committing transaction

	Coord	**Worker**	
	Update or Read-only	**Update**	**Read-Only**
Standard	2W,1F,1M(R/O),2M(U)	2W,2F,2M	0W,0F,1M
PA	2W,1F,1M(R/O),2M(U)	2W,2F,2M	0W,0F,1M
PC	2W,1F,1M(R/O),2M(U)	2W,1F,1M	0W,0F,1M

PA only helps in abort cases (not this one)
PC costs more writes on coord, but has fewer writes on workers

2PC – Problems

- 2 network round trips + synchronous logging ➔ high overheads
  - Particularly when Coord and Worker are far apart, i.e., in different data centers
- If Coord fails, Workers must wait, or somehow choose a new coordinator
- If Coord + 1 Worker fail, no way to recover
  - Coord may have told failed Worker about outcome, it may have exposed results

2PC sacrifices *availability* of system for *consistency*

2PC is probably not a good choice in a wide-area distributed setting

Due to possibility of network failures, and wide area latency

Alternatives: use a more complicated consensus protocol (e.g., Paxos), use deterministic execution, or relax consistency